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Charm production in charged current deep inelastic scattering at HERA

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ABSTRACT: Charm production in charged current deep inelastic scattering has been measured for the first time in $e^\pm p$ collisions, using data collected with the ZEUS detector at HERA, corresponding to an integrated luminosity of 358 pb^{-1} . Results are presented separately for e^+p and e^-p scattering at a centre-of-mass energy of $\sqrt{s} = 318 \text{ GeV}$ within a kinematic phase-space region of $200 \text{ GeV}^2 < Q^2 < 60000 \text{ GeV}^2$ and $y < 0.9$, where Q^2 is the squared four-momentum transfer and y is the inelasticity. The measured cross sections of electroweak charm production are consistent with expectations from the Standard Model within the large statistical uncertainties.

KEYWORDS: Heavy quark production, Lepton-Nucleon Scattering (experiments), QCD, Electroweak interaction

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1 Introduction

Measurements of heavy-flavour production serve as a good testing ground to investigate the predictive power of perturbative quantum chromodynamics (pQCD) as the large mass provides a natural hard scale. While charm production in neutral current deep inelastic scattering (NC DIS) and in photoproduction has been extensively studied at HERA, it has not been measured in charged current deep inelastic scattering (CC DIS) owing to its small cross section.

In CC DIS, single charm quarks in the final state already occur at the level of the Quark Parton Model (QPM) when either an incoming s or d quark is converted to a charm quark, or an incoming charm quark is converted to an s or d quark, as illustrated in figure 1 (i, ii). In the latter case, the single charm in the event arises from the associated charm quark in the proton remnant. In addition, single charm can arise from boson-gluon fusion (BGF) producing a $c\bar{s}$ ($c\bar{d}$) quark pair. In this case, the incoming virtual W boson fuses with a gluon from the proton. The gluon splits into a $s\bar{s}$ ($d\bar{d}$) or $c\bar{c}$ pair in the initial state, as shown in figure 1 (iii, iv). All these e^+p processes lead to the same final state, $e^+p \rightarrow \bar{\nu}_e c\bar{s}(\bar{d}) X$; this is also true for e^-p , $e^-p \rightarrow \nu_e \bar{c}s(d) X$. The characteristics of

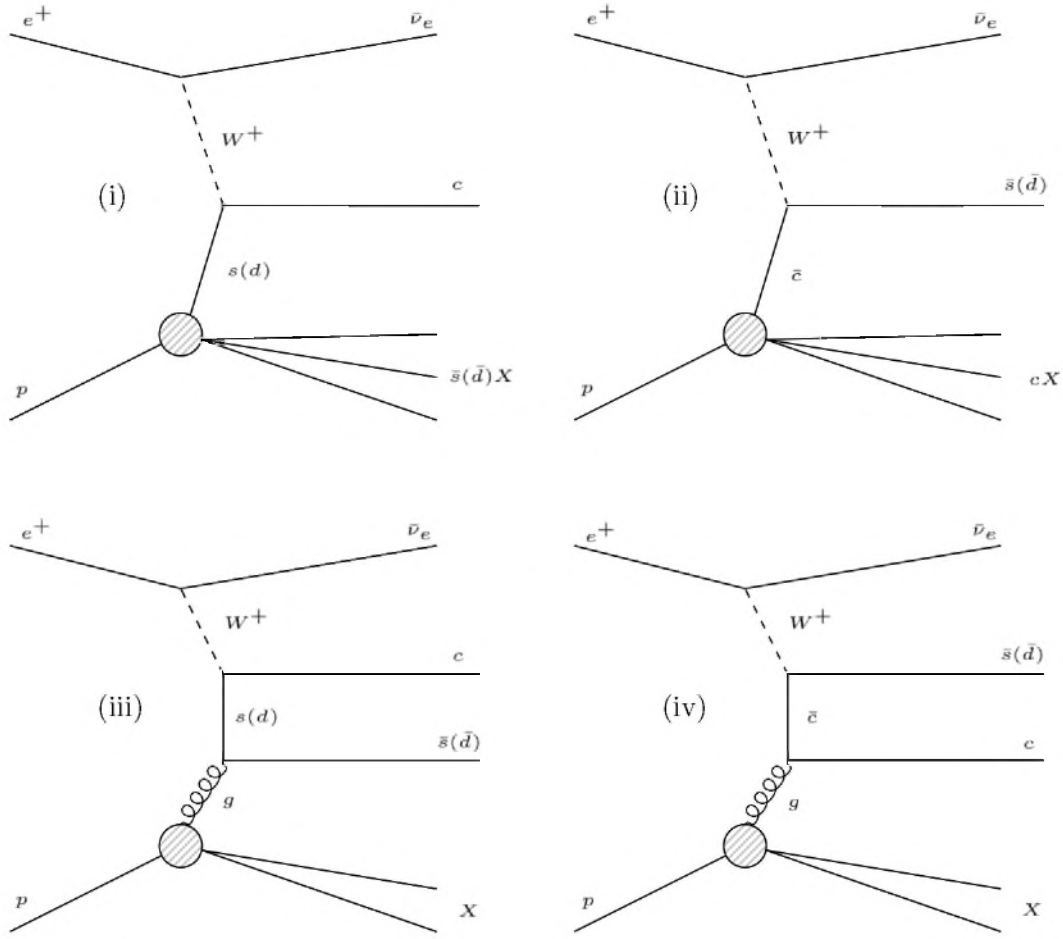


Figure 1. Feynman diagrams of charm-production subprocesses in e^+p collisions. The QPM process illustrated in (i) describes $s(d) \rightarrow c$ transitions. In the QPM process (ii) $\bar{c} \rightarrow \bar{s}(\bar{d})$, the charm in the final state arises from the associated charm quark in the proton remnant X . In the BGF processes, the incoming W boson couples to (iii) an $s\bar{s}(d\bar{d})$ or (iv) a $c\bar{c}$ pair from the gluon in the proton, producing a $c\bar{s}$ pair in the final state.

the events associated with these subprocesses and their association to particular kinematic configurations in the final state depend on the QCD scheme chosen, as detailed in the next section. The subprocess depicted in figure 1 (i) is directly sensitive to the strange-quark content of the proton and can be used to constrain it. However, the extraction of the relevant part of the cross section is model dependent.

In the $SU(3)$ flavour model, a perfect symmetry is assumed between the three light flavours, which results in equal quark densities for the sea quark components in nucleons. This symmetry is broken if the strange-quark density is suppressed by the mass of the strange quark, as happens in the well established strange-quark suppression in fragmentation [1]. This symmetry breaking can also occur in the initial state, depending on x ,

the fraction of the proton momentum carried by the interacting parton. For larger values of x , some support for this has been found experimentally, such as in dimuon production in charged current by the CCFR [2] and NuTeV [3], as well as the NOMAD [4] and CHORUS [5] neutrino scattering experiments. However, the interpretation of these measurements depends on nuclear corrections and charm fragmentation and no consensus has emerged on the exact level of suppression as a function of x . Additionally, the recent high-precision measurements of inclusive W and Z production by the ATLAS collaboration [6] report an unsuppressed strange sea in the low- x regime. A similar result was obtained in a combined global QCD analysis of inclusive W and Z data from both the ATLAS and CMS experiments [7]. This observation was also supported by the analysis of the ATLAS $W + c$ data [8]. However, the CMS $W + c$ data [9, 10] favour strangeness suppression also at low x . A re-evaluation of the LHC inclusive and $W + c$ measurements and the neutrino scattering measurements by NOMAD [4] and CHORUS [5] has been performed [11, 12], partly in an attempt to reconcile the factor-of-two discrepancy in the measured strange-quark densities. The resulting strange-quark parton distribution function (PDF) was reported to be inconsistent with the ATLAS fit [6].

This paper presents measurements of charm production in CC DIS in $e^\pm p$ collisions using data from the HERA II data-taking period. The electroweak contribution to charm-production cross sections is compared with several QCD schemes that are detailed in the following section.

2 Charm production in CC DIS at HERA

The kinematics of lepton-proton scattering can be described in terms of the Lorentz-invariant variables x_{Bj} , y and Q^2 . The variable Q^2 is the negative squared four-momentum of the exchange boson $-q^2 = -(k - k')^2$, where k and k' are the four-momenta of the incoming and outgoing lepton, respectively. The Bjorken- x scaling variable, x_{Bj} , is defined as $x_{\text{Bj}} = Q^2/(2p \cdot q)$, where p is the four-momentum of the incoming proton. The variable y is the inelasticity defined as $y = Q^2/(sx_{\text{Bj}})$, where s is the squared centre-of-mass energy of the collision.

The differential cross section of charm production in CC DIS at HERA, mediated by a W boson, can be expressed in terms of the proton structure functions F_2 , xF_3 and F_L as follows [13]

$$\frac{d^2\sigma(e^\pm p \rightarrow \bar{\nu}_e(\nu_e)W^\pm X)}{dx_{\text{Bj}}dQ^2} = \frac{G_F^2}{4\pi x_{\text{Bj}}} \frac{M_W^4}{(Q^2 + M_W^2)^2} [Y_+ F_2(x_{\text{Bj}}, Q^2) \mp Y_- x F_3(x_{\text{Bj}}, Q^2) - y^2 F_L(x_{\text{Bj}}, Q^2)], \quad (2.1)$$

where G_F is the Fermi coupling constant, M_W is the mass of the W boson and $Y_\pm = 1 \pm (1 - y)^2$. The contribution from the longitudinal structure function, F_L , vanishes except at values of $y \approx 1$. The basic electroweak single-charm production mechanisms have been outlined in section 1. In the leading-order plus parton-shower Monte Carlo (MC) simulation, the core electroweak matrix elements are based on the QPM graphs in figure 1 (i, ii) and BGF-like configurations in figure 1 (iii, iv) through initial-state parton

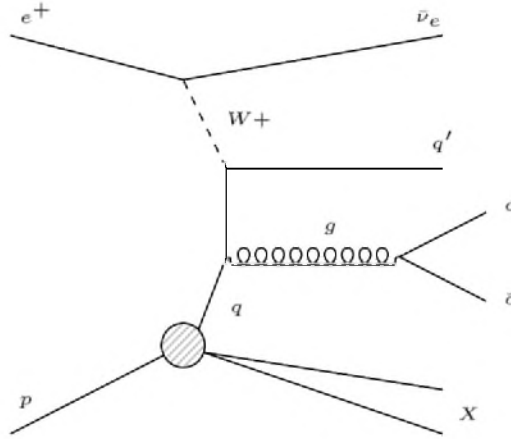


Figure 2. Example Feynman diagram of QCD charm process. The $c\bar{c}$ pairs from the final-state gluons, illustrated in the figure, are referred to as QCD charm in the text.

showering. In addition, other tree-level higher-order processes are also added through leading-log (LL) parton showering. The electroweak matrix elements involving only light quarks are complemented by occasional final-state gluon splitting into $c\bar{c}$ pairs in the parton shower, as depicted in figure 2, with a cutoff mimicking charm-mass effects. At the single-event level, if only one of the two charm quarks (or its resulting hadron) is detected and its charge is not measured (such as in the measurement technique used in this paper), then the contribution of this final-state QCD radiation is experimentally indistinguishable from electroweak production. The experimental measurement thus refers to a sum of all these processes, which make differing contributions to different regions of phase space, but cannot be disentangled with the presently available statistics.

In fixed-order QCD calculations, the final-state gluon-splitting contribution in figure 2 is formally of next-to-next-to-leading order (NNLO, $O(\alpha_s^2)$) and thus not included in the next-to-leading-order (NLO, $O(\alpha_s)$) QCD predictions considered in this work, even though its contribution can be substantial. Contributions from QPM-like (figure 1 (i, ii)) and BGF-like (figure 1 (iii, iv)) processes are separated by the virtuality of the quark entering the electroweak process in relation to the chosen factorisation scale. The NLO corrections to figure 1 (i, ii) arise in the form of initial- or final-state gluon radiation, or a vertex correction.

In the zero-mass variable-flavour-number scheme (ZM-VFNS) [14, 15], the charm part of the structure functions F_2^c and xF_3^c can be expressed in terms of different PDFs as follows

$$F_2^c = 2x_{\text{Bj}} \left\{ C_{2,q} \otimes \left[|V_{cd}|^2 (d + \bar{c}) + |V_{cs}|^2 (s + \bar{c}) \right] + 2(|V_{cd}|^2 + |V_{cs}|^2) C_{2,g} \otimes g \right\}, \quad (2.2)$$

$$xF_3^c = 2x_{\text{Bj}} \left\{ C_{3,q} \otimes \left[|V_{cd}|^2 (d - \bar{c}) + |V_{cs}|^2 (s - \bar{c}) \right] + (|V_{cd}|^2 + |V_{cs}|^2) C_{3,g} \otimes g \right\}, \quad (2.3)$$

in e^+p collisions, and

$$F_2^c = 2x_{\text{Bj}} \left\{ C_{2,q} \otimes \left[|V_{cd}|^2 (\bar{d} + c) + |V_{cs}|^2 (\bar{s} + c) \right] + 2(|V_{cd}|^2 + |V_{cs}|^2) C_{2,g} \otimes g \right\}, \quad (2.4)$$

$$xF_3^c = 2x_{\text{Bj}} \left\{ C_{3,q} \otimes \left[|V_{cd}|^2 (-\bar{d} + c) + |V_{cs}|^2 (-\bar{s} + cc) \right] + (|V_{cd}|^2 + |V_{cs}|^2) C_{3,g} \otimes g \right\}, \quad (2.5)$$

in e^-p collisions. Here $C_{i,j}$ is the coefficient function for parton j in structure-function F_i and d , s , c and g are respectively the down, strange, charm and gluon PDFs with the argument (x_{Bj}, Q^2) omitted. The parameters $|V_{ij}|$ are the Cabbibo-Kobayashi-Maskawa matrix elements. Part of the effects beyond NLO are resummed at next-to-leading log in the zero-mass approximation in this scheme.

In the NLO fixed-flavour-number (FFN) scheme [16, 17], charm-mass effects are treated explicitly up to $O(\alpha_s)$ in the matrix elements. In this scheme, there is no charm-quark content in the proton, thus the charm QPM graph in figure 1 (ii) and its associated higher-order corrections do not occur. This is compensated by a correspondingly larger gluon content in the proton, such that all initial-state charm contributions irrespective of scale are treated explicitly in the BGF matrix element (figure 1 (iv)). No resummation is performed.

In the FONLL-B scheme [18, 19], a general-mass variable-flavour-number scheme, charm-mass effects are accounted for by interpolating between the ZM-VFNS and FFN predictions, such that all mass effects are correctly included up to $O(\alpha_s)$.

The xFitter framework [20] was used to interface the theoretical predictions. Predictions in the FFN scheme were obtained from OPENQCDRAD [21] using the ABMP 16.3 NLO PDF sets [22, 23]. Predictions in the FONLL-B scheme were obtained from APFEL [24] with NNPDF3.1 [25]. The total uncertainties of the FFN and FONLL-B schemes were obtained by adding in quadrature the PDF, scale and charm-mass uncertainties.

In order to study the effects of strangeness suppression, the ZM-VFNS predictions were obtained from QCDNUM [26] with HERAPDF2.0 [27]. The strange-quark fraction, $f_s = \bar{s}/(\bar{d} + \bar{s})$, was chosen to vary in the range between a suppressed strange sea [28, 29] and an unsuppressed strange sea [6, 30]. In addition, two more variations of the assumptions about the strange sea were made. Instead of assuming that the strange contribution is a fixed fraction of the d -type sea, an x -dependent shape, $x\bar{s} = 0.5f'_s \tanh(-20(x - 0.07)) x\bar{D}$, where $x\bar{D} = x\bar{d} + x\bar{s}$, was used in which high- x strangeness is highly suppressed. This shape was suggested by HERMES measurements [31, 32]. The value of f'_s was also varied between $f'_s = 0.3$ and $f'_s = 0.5$. The ZM-VFNS prediction was also evaluated with the ATLAS- $epWZ16$ PDF sets [6].

3 Experimental set-up

This analysis was performed with data taken during the HERA II data-taking period in the years 2003–2007. During this period, electrons and positrons with an energy of 27.5 GeV collided with protons with an energy of 920 GeV at a centre-of-mass energy of $\sqrt{s} = 318$ GeV. The corresponding integrated luminosities are 173 pb^{-1} and 185 pb^{-1} for e^+p and e^-p collisions, respectively.

A detailed description of the ZEUS detector can be found elsewhere [33]. A brief outline of the components that are most relevant for this analysis is given below.

Charged particles were tracked in the central tracking detector (CTD) [34–36], the microvertex detector (MVD) [37] and the straw-tube tracker (STT) [38]. The CTD and the MVD operated in a magnetic field of 1.43 T provided by a thin superconducting solenoid. The CTD drift chamber covered the polar-angle¹ region $15^\circ < \theta < 164^\circ$. The MVD silicon tracker consisted of a barrel (BMVD) and a forward (FMVD) section. The BMVD provided polar angle coverage for tracks with three measurements from 30° to 150° . The FMVD extended the polar-angle coverage in the forward region to 7° . The STT covered the polar-angle region $5^\circ < \theta < 25^\circ$.

The high-resolution uranium-scintillator calorimeter (CAL) [39–42] consisted of three parts: the forward (FCAL), the barrel (BCAL) and the rear (RCAL) calorimeters. Each part was subdivided transversely into towers and longitudinally into one electromagnetic section (EMC) and either one hadronic section in RCAL (RHAC) or two in BCAL and FCAL (B/FHAC1 and B/FHAC2). The smallest subdivision of the calorimeter was called a cell. The CAL energy resolutions, as measured under test-beam conditions, were $\sigma(E)/E = 0.18/\sqrt{E}$ for electrons and $\sigma(E)/E = 0.35/\sqrt{E}$ for hadrons, with E in GeV.

The iron yoke surrounding the CAL was instrumented with proportional drift chambers to form the backing calorimeter (BAC) [43]. The BAC consisted of 5142 aluminium chambers inserted into the gaps between 7.3 cm thick iron plates (10, 9 and 7 layers in forecap, barrel and rearcap, respectively) serving as calorimeter absorber. The chambers were typically 5 m long and had a wire spacing of 1.5 cm. The anode wires were covered by 50 cm long cathode pads. The BAC was equipped with energy readout and position sensitive readout for muon tracking. The former was based on 1692 pad towers ($50 \times 50 \text{ cm}^2$), providing an energy resolution of $\sim 100\%/\sqrt{E}$, with E in GeV. The position information from the wires allowed the reconstruction of muon trajectories in two dimensions (XY in barrel and YZ in endcaps) with spatial accuracy of a few mm.

The luminosity was measured using the Bethe-Heitler reaction $ep \rightarrow e\gamma p$ by a luminosity detector which consisted of independent lead-scintillator calorimeter [44–46] and magnetic spectrometer [47] systems. The fractional systematic uncertainty on the measured luminosity was 2%.

4 Monte Carlo simulation

Inclusive CC DIS MC samples were generated to simulate the charm signal and light-flavour (LF) background. Neutral current DIS and photoproduction samples were used to simulate non-CC DIS backgrounds, which were found to be negligible after the CC selection defined below. The charged current events were generated with DJANGO 1.6 [48], using the CTEQ5D PDF sets [49] including QED and QCD radiative effects at the par-

¹The ZEUS coordinate system is a right-handed Cartesian system, with the Z axis pointing in the nominal proton beam direction, referred to as the “forward direction”, and the X axis pointing towards the centre of HERA. The coordinate origin is at the centre of the CTD. The pseudorapidity is defined as $\eta = -\ln(\tan \frac{\theta}{2})$, where the polar angle, θ , is measured with respect to the Z axis.

ton level. The ARIADNE 4.12 colour-dipole model [50] was used for parton showering. The Lund string model was used for hadronisation, as implemented in JETSET 7.4.1 [51]. The NC DIS events and photoproduction events were simulated by using DJANGO and HERWIG 5.9 [52], respectively.

5 Event selection and reconstruction

5.1 Reconstruction of kinematic variables

Charged current DIS at HERA produces a neutrino in the final state. The neutrino then escapes the ZEUS detector, resulting in a lack of information on the leptonic final state. Thus, the Lorentz-invariant kinematic variables must be defined with the hadronic final state. In the present analysis, this is done with the Jacquet-Blondel method, which assumes the four-momentum of the exchange-boson q to be equal not only to the difference in leptonic four-momentum $k - k'$ but also to that in hadronic four-momentum $p - p'$. Then, the invariant variables described in section 2 can be reconstructed as

$$y_{\text{JB}} = \frac{\sum_h (E - p_z)_h}{2E_{e,\text{beam}}}, \quad (5.1)$$

$$Q_{\text{JB}}^2 = \frac{p_{T,h}^2}{1 - y_{\text{JB}}}, \quad (5.2)$$

$$x_{\text{JB}} = \frac{Q_{\text{JB}}^2}{sy_{\text{JB}}}, \quad (5.3)$$

where $E_{e,\text{beam}}$ is the electron beam energy, $\sum_h (E - p_z)_h = \sum_i (E_i - p_{z,i})$ is the hadronic $E - P_z$ variable with the sum extending over the energies, E_i , and the longitudinal components of the momentum, $p_{z,i}$ of the reconstructed hadronic final-state particles, i . The quantity $p_{T,h} = |\sum_i p_{T,i}|$ is the total transverse momentum of the hadronic final state with $p_{T,i}$ being the transverse-momentum vector of the particle i . The mean value of the difference between the true and reconstructed kinematic variables was found to be within $\approx 1\%$ in the MC simulation study.

5.2 CC DIS selection

The ZEUS online three-level trigger system loosely selected CC DIS candidates based on calorimeter and tracking information [53, 54]. The triggered events were then required to pass the following offline selection criteria to reject non-CC DIS events:

- a kinematic selection cut was implemented at $200 \text{ GeV}^2 < Q_{\text{JB}}^2 < 60000 \text{ GeV}^2$ and $y_{\text{JB}} < 0.9$ to confine the sample into a region with good resolution of the kinematic quantities and small background;
- a characteristic of CC DIS events is the large missing transverse momentum, $p_{T,\text{miss}}$, in the calorimeter due to the undetected final-state neutrino. Events were required to have $p_{T,\text{miss}} > 12 \text{ GeV}$ and $p'_{T,\text{miss}} > 10 \text{ GeV}$, where $p'_{T,\text{miss}}$ is the missing transverse momentum, excluding measurements taken from the CAL cells adjacent to the forward beam hole;

- further background rejection is discussed in detail in a dedicated study of CC DIS at ZEUS in the e^+p scattering periods [55]. In addition, the remaining cosmic muons were removed by requiring the number of fired calorimeter cells $N_{\text{cell}} > 40$ and comparing fractions of energy deposited in the EMC and HAC. Events with energy deposited in the RCAL, $E_{\text{RCAL}} > 2 \text{ GeV}$, were rejected if $E_{\text{RHAC}}/E_{\text{RCAL}} > 0.5$. Events with energy in the BCAL, $E_{\text{BCAL}} > 2 \text{ GeV}$, were rejected if $E_{\text{BHAC}}/E_{\text{BCAL}} > 0.85$, $E_{\text{BHAC1}}/E_{\text{BCAL}} > 0.7$ or $E_{\text{BHAC2}}/E_{\text{BCAL}} > 0.4$. Events with energy in the FCAL, $E_{\text{FCAL}} > 2 \text{ GeV}$, were rejected if $E_{\text{FHAC}}/E_{\text{FCAL}} < 0.1$, $E_{\text{FHAC}}/E_{\text{FCAL}} > 0.85$, $E_{\text{FHAC1}}/E_{\text{FCAL}} > 0.7$ or $E_{\text{FHAC2}}/E_{\text{FCAL}} > 0.6$.

A total of 4093 events in e^+p data and 8895 events in e^-p data passed these selection criteria. Comparisons of data and MC at the event-level selection stage are shown in figures 3 and 4 for e^+p and e^-p , respectively. The MC distribution is consistent with the data in both the e^+p and e^-p periods. From MC studies, the charm contribution to the CC events is expected to be about 25% in the e^+p periods and 12% in the e^-p periods and similar for both periods in terms of numbers of events.

5.3 Charm selection and signal extraction

Charm quarks in CC DIS events were tagged by using an inclusive lifetime method [56, 57]. In CC DIS at HERA, LF production has the highest production rate and is the major source of background. The lifetime method uses the measurement of the decay length of the heavy-flavour (HF) particle to discriminate between signal and background contributions. The underlying principle of this method [56] is that ground-state HF particles travel on average a measurable distance before they decay at a secondary vertex.

Jets were reconstructed from energy-flow objects [58, 59], which combine the information from calorimetry and tracking, corrected for energy loss in the detector material. The k_T clustering algorithm [60] was used with a radius parameter $R = 1$ in the longitudinally invariant mode [61, 62]. The E-recombination scheme, which produces massive jets whose four-momenta are the sum of the four-momenta of the clustered objects, was used. Events were selected if they contained at least one jet with transverse energy, E_T^{jet} , greater than 5 GeV and within the jet pseudorapidity range $-2.5 < \eta^{\text{jet}} < 2.0$ (1.5).² These selection criteria constrained the kinematic phase-space region of this analysis, along with the kinematic selection criteria at the event-level selection stage.

Tracks from the selected jets were required to have a transverse momentum, $p_T^{\text{trk}} > 0.5 \text{ GeV}$, and the total number of hits in the MVD, $N_{\text{MVD}}^{\text{trk}} \geq 4$ to reduce the effect of multiple scattering and ensure a good spatial resolution. If more than two such tracks were associated with the jet, a secondary-vertex candidate was fitted from the selected tracks using a deterministic annealing filter [63–65]. This fit provided the vertex position and its error matrix as well as the hadronic invariant mass, M_{secvtx} , of the charged tracks associated with the reconstructed vertex. The charged-pion mass was assumed for all tracks when

²The tracking efficiency and resolution in the forward region $\eta^{\text{jet}} > 1.5$ suffered in the 2005 (e^-p) data-taking period as the STT was turned off during this time. Thus, the jets from this period were required to satisfy a tighter η^{jet} upper limit $\eta^{\text{jet}} = 1.5$.

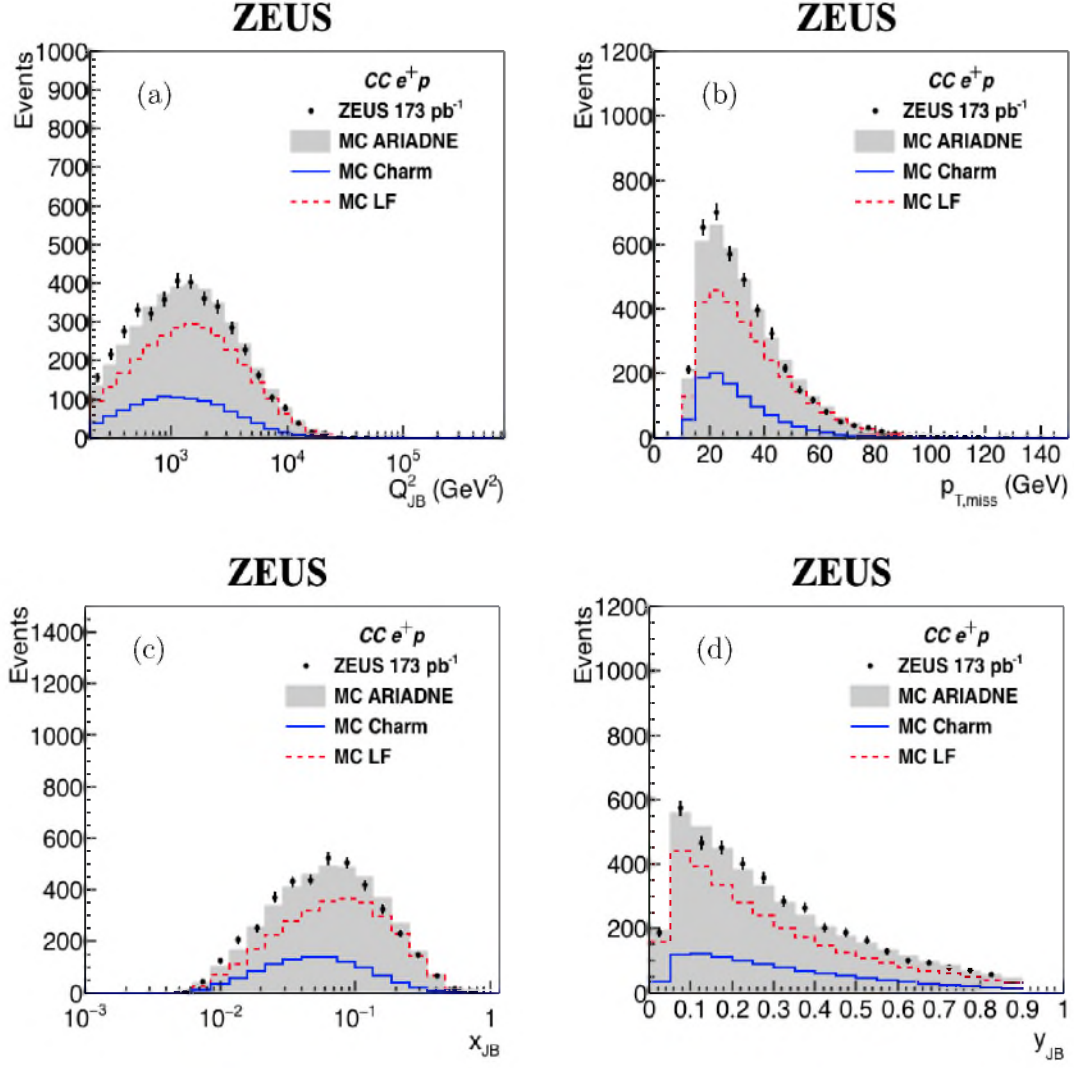


Figure 3. Comparison between data (dots) and MC (histogram) in kinematic variables (a) Q_{JB}^2 , (b) $p_{T,miss}$, (c) x_{JB} and (d) y_{JB} for e^+p collisions. The vertical error bars represent the statistical uncertainty in the data. “MC Charm” represents events with charm or anticharm quarks involved in the hard CC reaction either in the initial or final state. “MC LF” represents the contribution from light-flavoured events, i.e. with no heavy-flavour particles occurring in the event.

calculating the vertex mass. The secondary-vertex candidates were required to satisfy the following criteria:

- $N_{secvtx}^{trk} \geq 3$,
- $\chi^2/N_{dof} < 6$,
- $|z_{secvtx}| < 30$ cm,
- $M_{secvtx} < 6$ GeV,
- $\sqrt{\Delta x^2 + \Delta y^2} < 1$ cm,

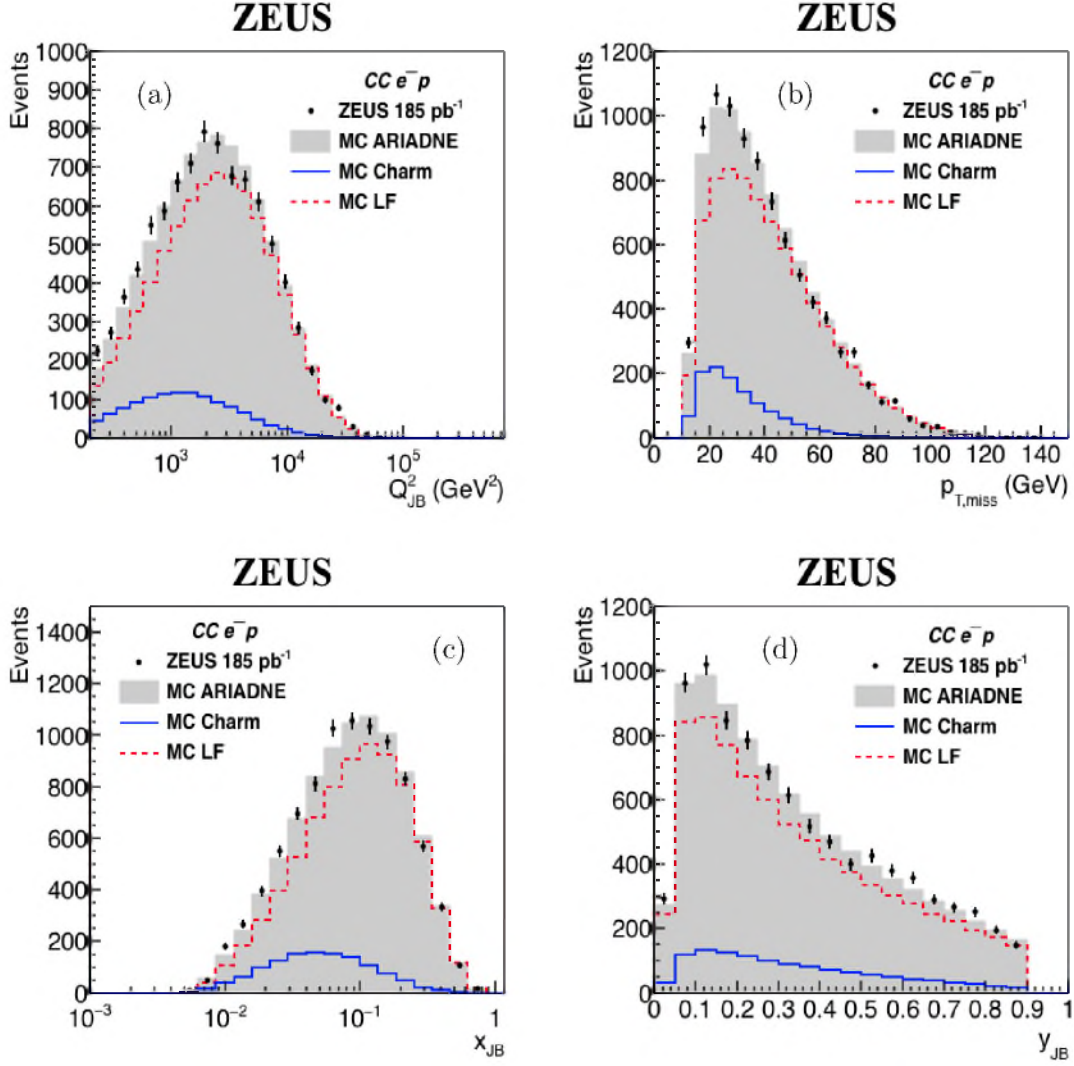


Figure 4. Comparison between data (dots) and MC (histogram) in kinematic variables (a) Q_{JB}^2 , (b) $p_{T,miss}$, (c) x_{JB} and (d) y_{JB} for e^-p collisions. The vertical error bars represent the statistical uncertainty in the data. “MC Charm” represents events with charm or anticharm quarks involved in the hard CC reaction either in the initial or final state. “MC LF” represents the contribution from light-flavoured events, i.e. with no heavy-flavour particles occurring in the event.

where N_{secvtx}^{trk} is the number of tracks used to reconstruct the vertex, χ^2/N_{dof} is the goodness of the vertex fitting, z_{secvtx} is the Z -coordinate of the secondary vertex and Δx , Δy are the X - and Y -displacement of the secondary vertex from the primary interaction vertex. These selection criteria ensure a good fit quality and high acceptance of the CTD and MVD for tracks used to reconstruct the vertices. The requirement on the track multiplicity was implemented in order to reduce the number of background vertices. Figures 5 and 6 show the distributions of the chosen jets and secondary-vertex candidates for the e^+p and e^-p periods, respectively.

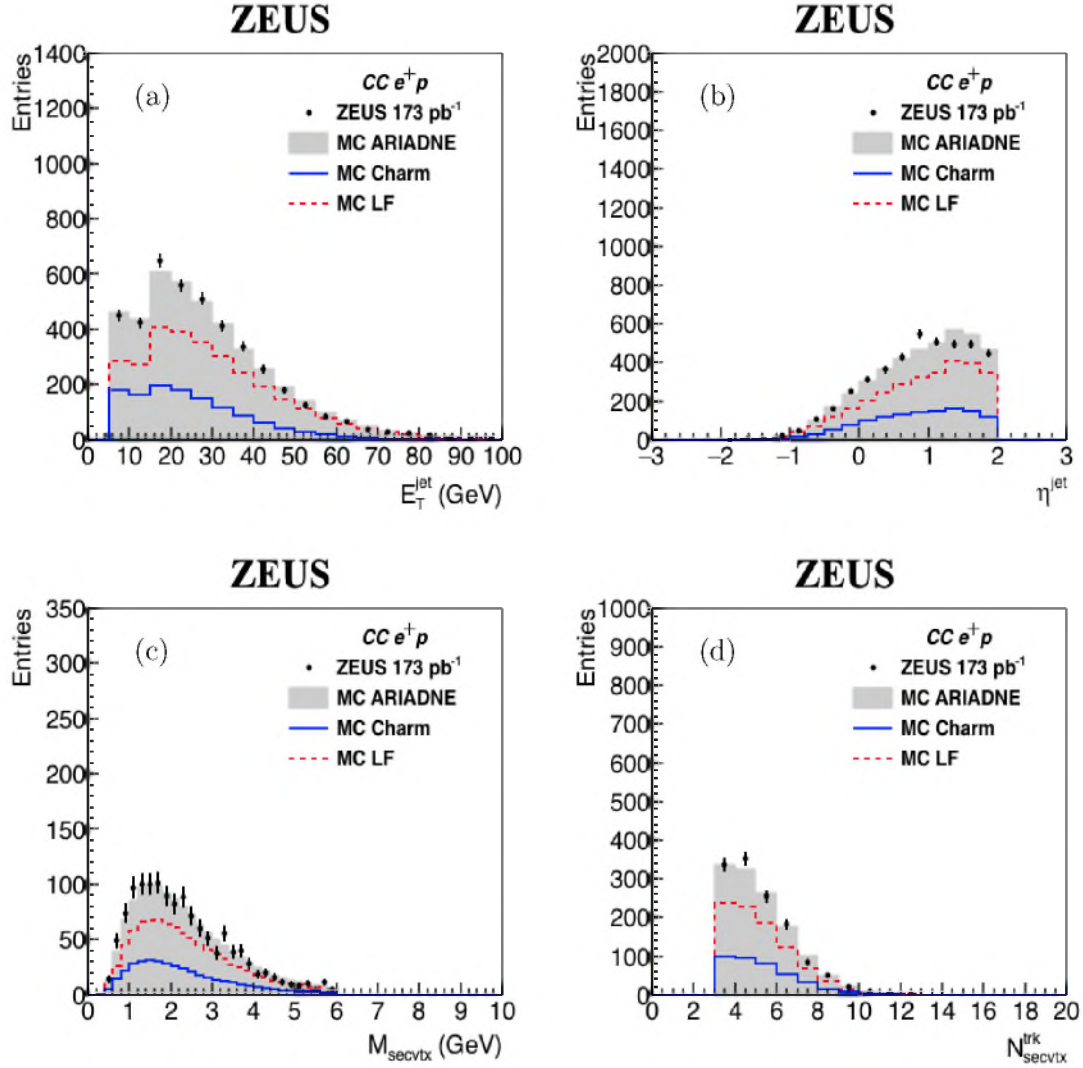


Figure 5. Comparison between data (points with vertical error bars) and MC (histogram) for jet and secondary-vertex distributions: (a) E_T^{jet} , (b) η^{jet} , (c) M_{secvtx} and (d) $N_{\text{trk}}^{\text{secvtx}}$ for e^+p collisions. The labels are the same as in figures 3 and 4.

The transverse decay length of the selected secondary vertices was projected onto the jet axis. Due to the finite resolution of the MVD and the prompt production of LF particles, the distributions of the 2D decay length (L_{xy}) and the significance of the decay length ($S = L_{xy}/\delta L_{xy}$) for LF jets were symmetric. In contrast, the distributions for HF jets, in this case containing charmed particles, were asymmetric, as illustrated in figures 7 and 8 (a, b). A very small contribution from beauty is also shown; this is treated as background. This enabled the LF background to be suppressed by subtracting the negative decay-length distribution from the positive decay-length distribution.

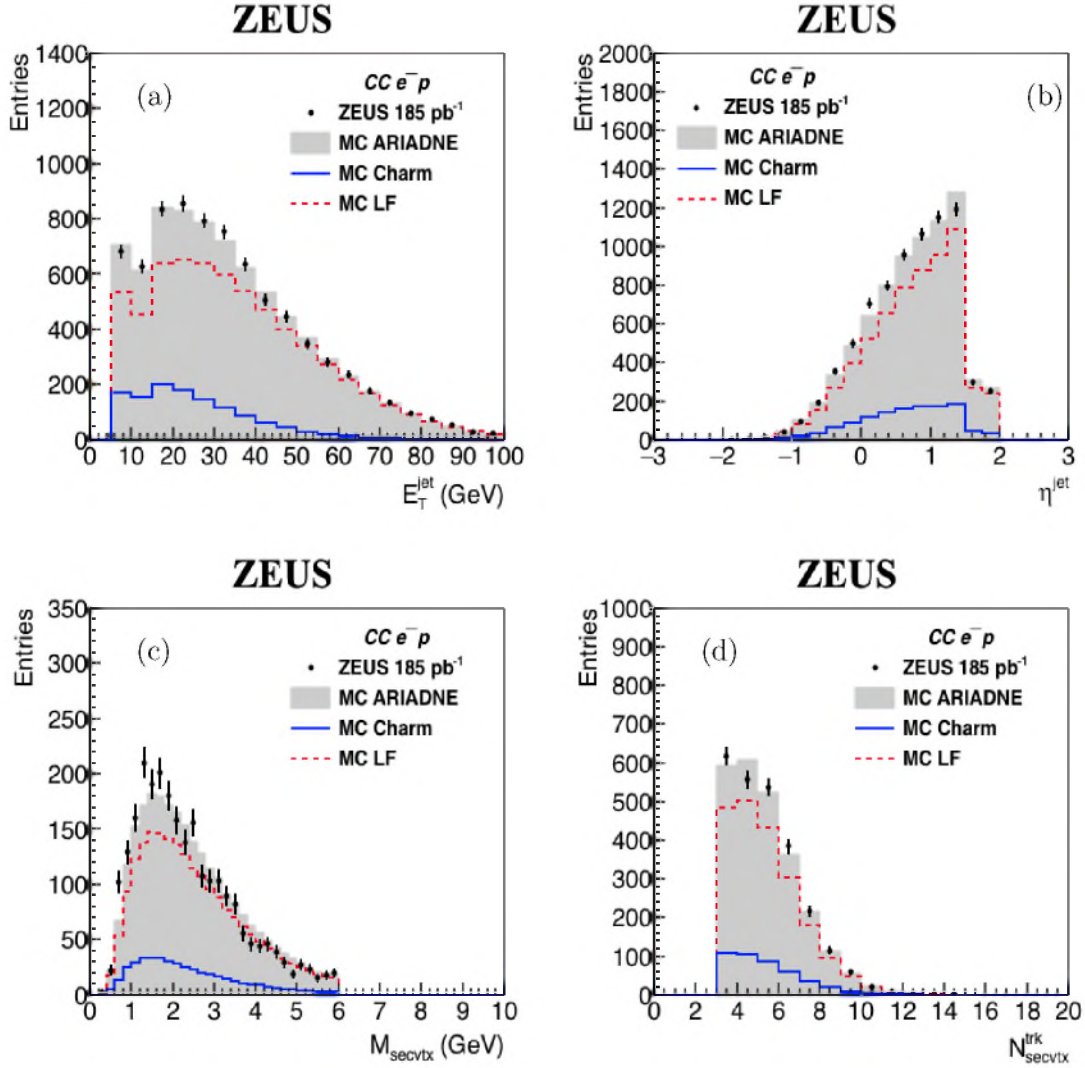


Figure 6. Comparison between data (points with vertical error bars) and MC (histogram) for jet and secondary-vertex distributions: (a) E_T^{jet} , (b) η^{jet} , (c) M_{secvtx} and (d) $N_{\text{trk}}^{\text{secvtx}}$ for e^-p collisions. The labels are the same as in figures 3 and 4.

The region around $|L_{xy}| = 0$ or $|S| = 0$ is dominated by LF production, resulting in a large statistical uncertainty of the distribution due to subtraction of two large numbers. To optimise the precision of the extracted signal, vertex candidates were required to satisfy a significance threshold, $|S| > 2$. Figures 7 and 8 (c, d) illustrate the shape of the variable distributions after the background subtraction. The surviving events after the decay-length subtraction were used to extract charm cross sections in two bins of Q^2 .

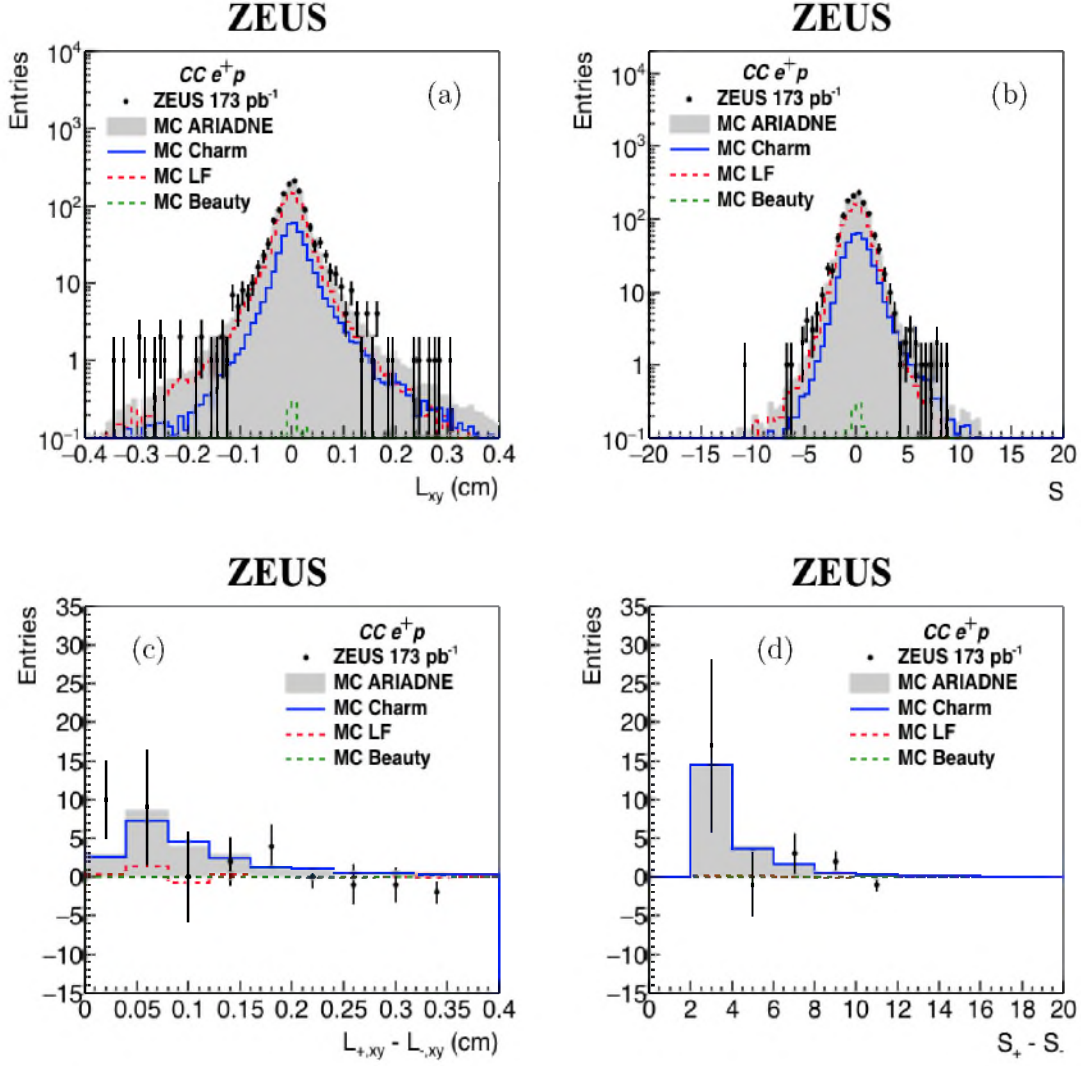


Figure 7. Comparison between data (points with vertical error bars) and MC (histogram) for e^+p collisions for distributions of (a) the 2D decay length L_{xy} and (b) significance S distribution and for distributions of the subtracted (c) decay-length $L_{+xy} - L_{-xy}$ and (d) significance $S_+ - S_-$ distribution. The labels are the same as in figures 3 and 4. “MC beauty” represents events with beauty but no charm quark.

6 Charm cross section

The lifetime method used in this analysis tags charm quarks regardless of their origin. Thus, the selected reactions include charm production from final-state gluon splitting, such as shown in figure 2, which is here denoted by QCD charm, in addition to the electroweak (EW) charm production discussed in section 2. In the present analysis, charm production was measured inclusively for $200 \text{ GeV}^2 < Q^2 < 60000 \text{ GeV}^2$ and $y < 0.9$. Additionally, to reflect the detector acceptance, a visible phase-space region was defined as: $200 \text{ GeV}^2 < Q^2 < 60000 \text{ GeV}^2$, $y < 0.9$, $E_T^{\text{jet}} > 5 \text{ GeV}$ and $-2.5 < \eta^{\text{jet}} < 2.0$. The limited statistics

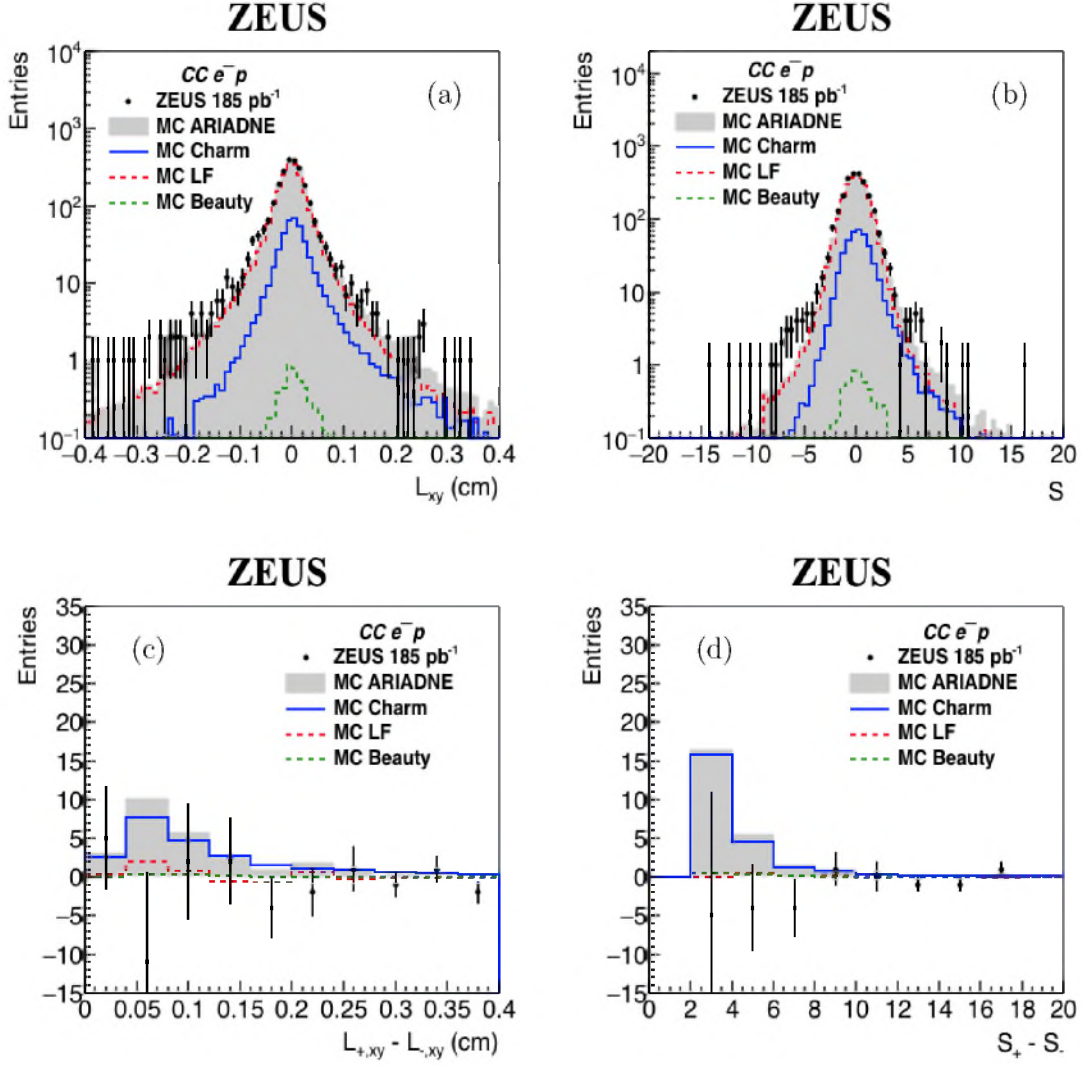


Figure 8. Comparison between data (points with vertical error bars) and MC (histogram) for e^+p collisions for distributions of (a) the 2D decay length L_{xy} and (b) significance S distribution and for distributions of the subtracted (c) decay-length $L_{+xy} - L_{-xy}$ and (d) significance $S_+ - S_-$ distribution. The labels are the same as in figures 3 and 4. “MC beauty” represents events with beauty but no charm quark.

and absence of a charm-charge determination prevented an experimental separation of the different theoretical contributions. The visible charm-jet cross section, $\sigma_{c,\text{vis}}$, was initially measured as follows:

$$\sigma_{c,\text{vis}} = \frac{N^{\text{data}} - N_{\text{bg}}^{\text{MC}}}{N_c^{\text{MC}}} \cdot \sigma_{c,\text{vis}}^{\text{MC}}, \quad (6.1)$$

where N^{data} is the reconstructed number of charm-jet candidates in the data after the $S_+ - S_-$ subtraction, $N_{\text{bg}}^{\text{MC}}$ is the background contribution and N_c^{MC} is the charm/anti-charm contribution estimated from the MC. Here $\sigma_{c,\text{vis}}^{\text{MC}}$ is the cross section of jets that

e^+p	MC Contribution (%)			
	$d \rightarrow c$	$s \rightarrow c$	$\bar{c} \rightarrow \bar{s}(\bar{d})$	$g \rightarrow c\bar{c}$
$\sigma_{c,\text{vis}}^{\text{MC}} + \sigma(g \rightarrow c\bar{c})$	9	45	40	6
$\sigma_{c,\text{EW}}^{\text{MC}} + \sigma(g \rightarrow c\bar{c})$	7	31	58	4

e^-p	MC Contribution (%)			
	$\bar{d} \rightarrow \bar{c}$	$\bar{s} \rightarrow \bar{c}$	$c \rightarrow s(d)$	$g \rightarrow c\bar{c}$
$\sigma_{c,\text{vis}}^{\text{MC}} + \sigma(g \rightarrow c\bar{c})$	3	45	40	12
$\sigma_{c,\text{EW}}^{\text{MC}} + \sigma(g \rightarrow c\bar{c})$	2	31	57	10

Table 1. MC contributions (%) of charm subprocesses to $\sigma_{c,\text{vis}}^{\text{MC}}$ and $\sigma_{c,\text{EW}}^{\text{MC}}$ as predicted by ARIADNE. The first two columns ($d \rightarrow c$ and $s \rightarrow c$ for e^+p collisions, for example) reflect the contributions from the QPM processes described in figure 1 (i) and a higher-order correction described in figure 1 (iii). The contribution of the final-state gluon splitting described in figure 2 enters the fourth column ($g \rightarrow c\bar{c}$).

are generated in the MC within the visible kinematic region and associated to a generated charm or anti-charm quark when $\sqrt{\Delta\phi^2 + \Delta\eta^2} < 1$, where $\Delta\phi$ and $\Delta\eta$ are, respectively, the azimuthal angle and pseudorapidity difference between the jet and the charm quark. Each charm quark was associated to the jet with the highest E_T^{jet} satisfying the above criteria and each such jet entered the visible cross section. The different processes contributing to $\sigma_{c,\text{vis}}^{\text{MC}}$ as predicted by MC are given in table 1.

The EW contribution in the charm-quark signal, $\sigma_{c,\text{vis}}^{\text{EW}}$, should be evaluated by subtracting the QCD contribution from gluon splitting (figure 2). However, the prediction from ARIADNE 4.12, like any prediction from gluon splitting in the massless mode with cutoff, cannot be considered to be reliable. Since the contribution predicted by ARIADNE (see table 1) is both small and imprecise, it was not subtracted but rather included in the systematic uncertainties. The visible jet cross section was extrapolated and converted to the total EW cross section via a factor C_{ext} , calculated from the ratio of the number of charm events generated in the full kinematic range, $N_{\text{gen}}^{\text{EW}}$, to the number of charm jets of EW origin within the visible kinematic region, $N_{\text{vis}}^{\text{EW}}$:

$$C_{\text{ext}} = \frac{N_{\text{gen}}^{\text{EW}}}{N_{\text{vis}}^{\text{EW}}}. \quad (6.2)$$

The resulting total EW charm cross section, $\sigma_{c,\text{EW}}$, is then given by

$$\begin{aligned} \sigma_{c,\text{EW}} &= C_{\text{ext}} \sigma_{c,\text{vis}} \\ &= \frac{N_{\text{gen}}^{\text{EW}}}{N_{\text{vis}}^{\text{EW}}} \frac{N^{\text{data}} - N_{\text{bg}}^{\text{MC}}}{N_c^{\text{MC}}} \sigma_{c,\text{vis}}^{\text{MC}}. \end{aligned} \quad (6.3)$$

This is predicted by the ARIADNE MC to be approximately 9 pb.

7 Systematic uncertainties

Although the statistical power of the current data is limited, it is important for future studies to understand the limitations of the current method by careful evaluation of the systematic uncertainties. The sources of uncertainty and their estimated effects on the total EW charm cross sections provided in parentheses ($\delta\sigma^{e^+p}$, $\delta\sigma^{e^-p}$) are:

- Secondary vertex rescaling
The MC samples used in this analysis produced a higher fraction of events with secondary vertices than the data. For the nominal result, N_c^{MC} and $N_{\text{bg}}^{\text{MC}}$ in eq. (6.1) were reduced proportionally. For the systematic uncertainty, only $N_{\text{bg}}^{\text{MC}}$ was rescaled (-1.2 pb, $+0.9$ pb).
- EW charm fraction
The MC predictions of the QCD contribution (figure 2) shown in table 1 of $+6\%$ for e^+p collisions and $+12\%$ for e^-p collisions were taken as systematic uncertainty (-0.6 pb, -1.1 pb).
- LF background
The uncertainty due to the remaining LF background was estimated by varying it by $\pm 30\%$ [56] (± 0.1 pb, ± 0.3 pb).
- CC DIS selection
The uncertainty due to the CC selection cuts was estimated by varying these cuts as in the previous ZEUS analysis [66] (± 0.2 pb, ± 0.1 pb).
- Jet energy scale
The part of the transverse jet energy measured in the calorimeter in the MC was varied by its estimated uncertainty of $\pm 3\%$ (± 0.0 pb, ± 0.1 pb).

These uncertainties were added in quadrature. The uncertainty in the ZEUS luminosity measurement is $\pm 2\%$ and was not included in the results.

In addition, the effect of the significance cut, $|S| > 2$, was studied. Small changes in the value of the significance cut resulted in large changes of the extracted signal. This was found to be due to statistical fluctuations in the number of events in the region close to the $|S|$ lower cut value. From a dedicated study, the effects on the cross sections were found to be as large as ± 5 pb. As this result was still strongly affected by statistical fluctuations, which have been included in the quoted statistical uncertainty, it was not included in the systematic uncertainty.

Additionally, the uncertainty in the secondary-vertex selection method was estimated by reducing the requirement on the number of tracks, $N_{\text{secvtx}}^{\text{trk}}$, from three to two. The effects on the cross sections were found to be as large as $+3$ pb. This was again strongly affected by statistical fluctuations and not included in the systematic uncertainty.

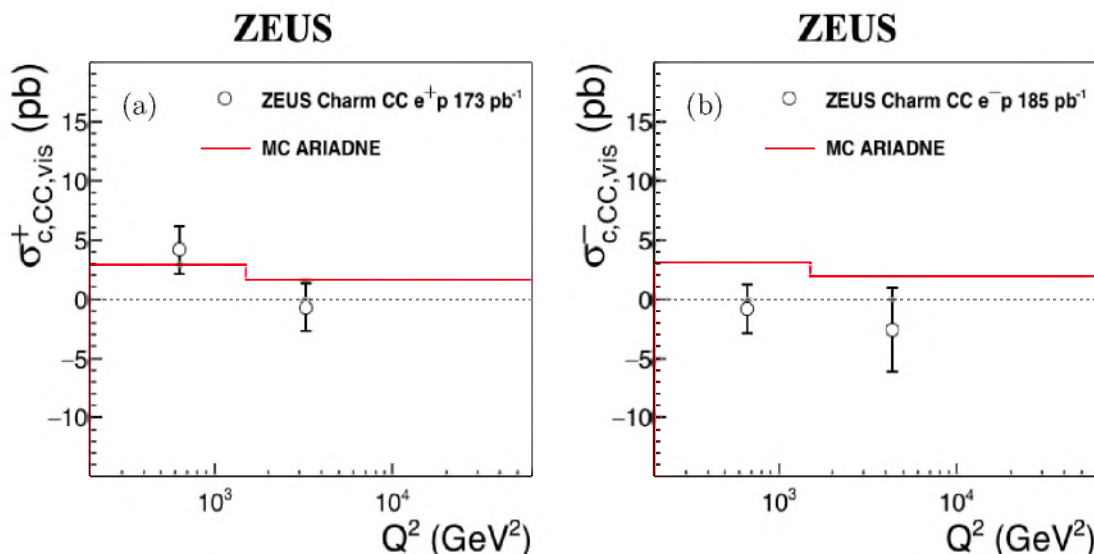


Figure 9. The visible charm cross sections, $\sigma_{c,\text{vis}}$, in two bins in Q^2 for (a) e^+p and (b) e^-p collisions. The vertical error bars show the total uncertainties; the systematic uncertainties are negligible. The solid lines represent predictions obtained with the ARIADNE MC.

8 Results

The charm-jet cross sections in CC DIS in $e^\pm p$ collisions were measured in the visible kinematic phase space of $200 \text{ GeV}^2 < Q^2 < 60000 \text{ GeV}^2$, $y < 0.9$, $E_T^{\text{jet}} > 5 \text{ GeV}$ and $-2.5 < \eta^{\text{jet}} < 2.0$ to be

$$\begin{aligned}\sigma_{c,\text{vis}}^+ &= 4.0 \pm 2.8 \text{ (stat.) } {}^{+0.1}_{-0.6} \text{ (syst.) pb,} \\ \sigma_{c,\text{vis}}^- &= -3.0 \pm 3.8 \text{ (stat.) } {}^{+0.5}_{-0.1} \text{ (syst.) pb,}\end{aligned}$$

where the superscript \pm denotes the charge of the incoming lepton. In addition, the cross sections were obtained for two separate Q^2 bins, $200 \text{ GeV}^2 < Q^2 < 1500 \text{ GeV}^2$ and $1500 \text{ GeV}^2 < Q^2 < 60000 \text{ GeV}^2$, and are shown in figure 9.

The total electroweak charm cross sections were found, following eq. (6.3), to be

$$\begin{aligned}\sigma_{c,\text{EW}}^+ &= 8.5 \pm 5.5 \text{ (stat.) } {}^{+0.2}_{-1.3} \text{ (syst.) pb,} \\ \sigma_{c,\text{EW}}^- &= -5.7 \pm 7.2 \text{ (stat.) } {}^{+1.0}_{-1.2} \text{ (syst.) pb.}\end{aligned}$$

The QCD contribution to charm production was introduced as an additional systematic uncertainty. Theory predictions obtained at NLO QCD with the FFN and FONLL-B schemes are compared to the data in bins of Q^2 in figure 10. Table 2 provides the experimental values of the cross sections $\sigma_{c,\text{vis}}$ and $\sigma_{c,\text{EW}}$ for the two bins in Q^2 . The contributions of the charm production subprocesses to the final EW cross section in each bin were estimated in the ARIADNE MC, FFN and FONLL-B predictions and are listed in table 3. In table 4, the theory predictions from the FFN and FONLL schemes are shown with the total uncertainties, as discussed in section 2. The predictions from the ZM-VFNS scheme with varied

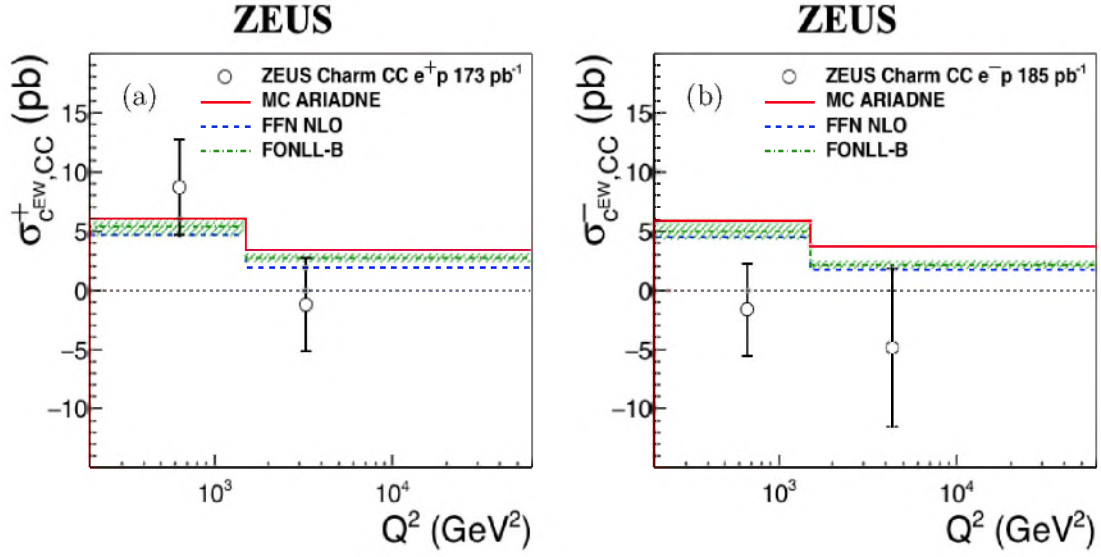


Figure 10. The EW charm cross sections, $\sigma_{c^{\text{EW}}}$, in two bins of Q^2 for (a) e^+p and (b) e^-p collisions. The vertical error bars show the total uncertainties; the included systematic uncertainties are negligible. The solid lines represent predictions obtained with the ARIADNE MC. The dashed and dashed-dotted lines represent, respectively, predictions from the FFN and FONLL-B schemes. Hatched bands are the total uncertainty in the predictions from FONLL-B schemes.

Q^2 range (GeV ²)	$\sigma_{c,\text{vis}}$ (pb)					$\sigma_{c^{\text{EW}}}$ (pb)				
e^+p										
200–1500	4.1	±2.0	(stat.)	$^{+0.1}_{-0.6}$	(syst.)	8.7	±4.1	(stat.)	$^{+0.2}_{-1.4}$	(syst.)
1500–60000	−0.7	±2.0	(stat.)	$^{+0.2}_{-0.0}$	(syst.)	−1.2	±3.9	(stat.)	$^{+0.3}_{-0.3}$	(syst.)
e^-p										
200–1500	−0.9	±2.1	(stat.)	$^{+0.2}_{-0.0}$	(syst.)	−1.7	±3.9	(stat.)	$^{+0.3}_{-0.3}$	(syst.)
1500–60000	−2.6	±3.5	(stat.)	$^{+0.5}_{-0.1}$	(syst.)	−4.8	±6.7	(stat.)	$^{+0.9}_{-0.8}$	(syst.)

Table 2. Measured visible cross sections, $\sigma_{c,\text{vis}}$, and EW cross section, $\sigma_{c^{\text{EW}}}$, for two Q^2 bins.

strange-quark fraction are given in table 5. A further reduction of the theory uncertainty can be achieved in the future by including NNLO corrections [67].

The theory predictions in table 3 suggest that the most interesting subprocess, namely the QPM process depicted in figure 1 (i), contributes about 30–50% to the final EW cross section, depending on the kinematic range and QCD scheme used. In general, the data are well described by the theory predictions, however the large experimental uncertainties prevent a discrimination between the different models.

e^+p	Contribution (%)					
	$200 < Q^2 < 1500 \text{ GeV}^2$			$1500 < Q^2 < 60000 \text{ GeV}^2$		
	$d \rightarrow c$	$s \rightarrow c$	$\bar{c} \rightarrow \bar{s}(\bar{d})$	$d \rightarrow c$	$s \rightarrow c$	$\bar{c} \rightarrow \bar{s}(\bar{d})$
ARIADNE MC	6	36	58	10	26	64
FFN NLO ABMP16.3	8	49	43	16	43	41
FONLL-B NNPDF3.1	8	43	49	12	37	51

e^-p	Contribution (%)					
	$200 < Q^2 < 1500 \text{ GeV}^2$			$1500 < Q^2 < 60000 \text{ GeV}^2$		
	$\bar{d} \rightarrow \bar{c}$	$\bar{s} \rightarrow \bar{c}$	$c \rightarrow s(d)$	$\bar{d} \rightarrow \bar{c}$	$\bar{s} \rightarrow \bar{c}$	$c \rightarrow s(d)$
ARIADNE MC	3	37	60	2	29	69
FFN NLO ABMP16.3	4	51	45	5	49	46
FONLL-B NNPDF3.1	4	43	53	4	33	63

Table 3. Contribution (%) of charm subprocesses to EW charm production in CC DIS in both e^+p and e^-p collisions, as predicted by the ARIADNE MC and FFN and FONLL-B schemes. The labels are explained in table 1. Additionally for the MC and FONLL-B scheme, the contribution of the QPM process in figure 1 (ii) enters in the third column ($\bar{c} \rightarrow \bar{s}(\bar{d})$) with a higher-order correction from the BGF process in figure 1 (iv). For the FFN scheme, the process described in figure 1 (ii) does not participate. Thus the content of the third column is provided by the BGF process of figure 1 (iv) only.

Q^2 range (GeV^2)	NLO Predictions (pb)							
	FFN ABMP16.3				FONLL-B NNPDF3.1			
	σ	uncertainties			σ	uncertainties		
		PDF	scale	mass		PDF	scale	mass
e^+p								
200 – 1500	4.72	± 0.05	$^{+0.31}_{-0.23}$	± 0.02	5.37	± 0.21	$^{+0.68}_{-0.73}$	± 0.00
1500–60000	1.97	± 0.03	$^{+0.18}_{-0.13}$	± 0.01	2.66	± 0.23	$^{+0.37}_{-0.26}$	± 0.00
e^-p								
200 – 1500	4.50	± 0.05	$^{+0.31}_{-0.23}$	± 0.02	4.98	± 0.22	$^{+0.66}_{-0.71}$	± 0.00
1500–60000	1.73	± 0.03	$^{+0.18}_{-0.13}$	± 0.01	2.16	± 0.22	$^{+0.33}_{-0.21}$	± 0.00

Table 4. The NLO theory predictions from the FFN and FONLL-B schemes with their full uncertainties. The scale uncertainty was obtained by varying the renormalisation and factorisation scales simultaneously up and down by a factor two. The mass uncertainty was obtained by varying the charm mass, $m_c(m_c)$, within its uncertainties $m_c(m_c) = 1.28 \pm 0.03 \text{ GeV}$.

Q^2 range (GeV ²)	NLO Predictions (pb)					
	HERAPDF2.0					ATLAS- <i>epW</i> Z16
	$f_s = 0.4$ (nominal)	$f_s = 0.3$	$f_s = 0.5$	$f'_s =$ HERMES-	$f'_s =$ HERMES+	
e^+p						
200 – 1500	5.67	5.40	5.96	5.05	5.38	6.41
1500–60000	2.57	2.47	2.65	2.16	2.20	3.07
e^-p						
200 – 1500	5.41	5.15	5.70	4.79	5.12	6.14
1500–60000	2.30	2.21	2.37	1.89	1.93	2.78

Table 5. The NLO ZM-VFNS predictions with varied strange-quark fraction f_s . Additionally, two x -dependent strange quark fractions were used as suggested by the HERMES collaboration. The ZM-VFNS predictions were also evaluated with the ATLAS-*epW* Z16 PDF set with an unsuppressed strange-quark content.

9 Summary and outlook

Measurements of charm production in charged current deep inelastic scattering in $e^\pm p$ collisions have been performed based on HERA II data with an integrated luminosity of 358 pb^{-1} , which corresponds to e^+p collisions with an integrated luminosity of 173 pb^{-1} and e^-p collisions with an integrated luminosity of 185 pb^{-1} . Visible charm-jet cross sections for each lepton beam type were measured within a kinematic region $200 \text{ GeV}^2 < Q^2 < 60000 \text{ GeV}^2$, $y < 0.9$, $E_T^{\text{jet}} > 5 \text{ GeV}$ and $-2.5 < \eta^{\text{jet}} < 2.0$. They were extrapolated to the EW cross sections given in the kinematic range $200 \text{ GeV}^2 < Q^2 < 60000 \text{ GeV}^2$ and $y < 0.9$. Theoretical predictions with several assumptions about the strange-quark content of the proton and using different heavy-flavour schemes were found to be consistent with the data within the large experimental uncertainties. The analysis presented here shows the potential of DIS measurements to increase the knowledge about the strange-quark content of the proton. Future lepton-ion collider projects such as the electron-ion collider [68] or LHeC [69] will have much higher luminosity than HERA, accompanied by improved vertex detection capabilities. These projects should then be able to make an important contribution to the knowledge of the strange-quark content of the proton.

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